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Numerical simulation of sediment deposition thickness at Beidaihe International Yacht Club

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Abstract: The finite element method (FEM) was used to simulate sediment hydrodynamics at the Beidaihe International Yacht Club, and a two-dimensional model was established. The sediment movement and deposition were analyzed under many tidal conditions in conjunction with the hydrological regime of the Daihe River. The peak value of the sediment deposition thickness appears in the main channel and around the estuary. The sediment deposition thickness is essentially constant and relatively small in the project area. The sediment deposition thickness in the main channel, in the yachting area, and around the hotel is greater than the other areas in the project. Regular excavation and dredging of the channel is the best measure for mitigating the sedimentation.

Key words: *Beidaihe International Yacht Club; numerical simulation; sediment deposition thickness*

1 Introduction

The Beidaihe International Yacht Club Resort is located on the Daihe River shore, the vacation spot of Beidaihe. The total land area of the project is about 1.78×10^5 m^2, and the total construction area is about 6×10^4 m^2. The construction area of the yacht club is about 5×10^3 m^2. The total yachting area is about 1.23×10^5 m^2, the average depth is about 4.4 m, the water volume is about 5.43×10^5 m^3, and the number of yacht berths is 100.

The yachting area contains a series of islands. The building and the yacht club beside the water are linked by a continuous watercourse. The club is located in the Daihe River estuary. The Daihe River originates in Mayigou, in Beizhuang Township, Funing County. The difference in height over the entire course of the Daihe River is 200 m, and the general trend of the longitudinal slope is 0.11% upstream and 0.05% downstream. Upstream, the river bed is wide and shallow and has much gravel, but in the lower reaches it is narrow and deep and has multiple types of sediments. Especially in the flood season, floods carry a lot of sediment. The sediment easily fills up the channel as the velocity changes according to the tides in the tidal estuary. A rise of the river bed of the project area (the branch channels) and a decrease in the

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depth can affect the normal running of yachts, especially sailboats.

It is important to ensure that the yachting area meets the requirements of navigation and parking, has good water quality, and is free of serious sedimentation. Thus, it is necessary to examine questions of hydrodynamics, the water environment, and sediment movement in the yachting area, the surrounding sea, and the Daihe River. This article presents a study on the sediment hydrodynamics in the project area, using a sediment mathematical model. The research lays a foundation for the further demonstration and regulation of the whole project.

2 Sediment mathematical model

2.1 Basic sediment control equation

After completing the relevant hydrodynamic and regional flow field simulation, we selected the basic sediment convection-diffusion equation (Letter et al. 1998), which was proposed by Ariathurai, MacArthur, and Krone in 1977:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\alpha_1 C+\alpha_2 \tag{1}$$

where C is sediment concentration (kg/m^3), t is time (s), u is the velocity in the x direction (the main flow direction) (m/s), v is the velocity in the y direction (m/s), D_x is the effective diffusion coefficient in the x direction (m^2/s), D_y is the effective diffusion coefficient in the y direction (m^2/s), α_1 is the source coefficient (s^{-1}), and α_2 is the equilibrium concentration of the source term. This equation can be simplified and transformed into the finite element form through the quadratic shape function (Lin 2006; Liu 2005):

$$\sum_{n_\mathrm{e}=1}^{N_\mathrm{E}}\iint_{D_{n_\mathrm{e}}}\left[N_j\left(Q+u\frac{\partial\hat{C}}{\partial x}+v\frac{\partial\hat{C}}{\partial y}-\alpha_1\hat{C}\right)+D_x\frac{\partial\hat{C}}{\partial x}\frac{\partial N_j}{\partial x}+D_y\frac{\partial\hat{C}}{\partial y}\frac{\partial N_j}{\partial y}\right]\mathrm{d}x\mathrm{d}y+\sum_{i=1}^{N_\mathrm{L}}\int_{\zeta}N_j q_i^\mathrm{s}\mathrm{d}\zeta=0 \tag{2}$$

where N_E is the total number of the model particle elements, n_e is the computed number of the model particle elements, D_{n_e} is the area of the model particle elements, N_j is the quadratic shape function of the model particle elements, $\hat{C}$ is the element critical concentration obtained by the shape function and the nodes of concentration values C, N_L is the total number of border node strings, i is the number of border node strings, ζ is the local coordinate, q_i^s is the source flux of the ith border, and Q is flow discharge.

2.2 Division of computational grids

The sediment model calculation area of the Beidaihe International Yacht Club stretches from 2 000 m upstream the Daihe River estuary to the semi-circular region in the sea whose radius is 1 000 m. This study divided the finite element meshes according to the topography of the river and the seabed, as well as the border characteristics. The quadrilateral elements were used on the meshes, in an attempt to make the grid reflect the tide and river flows appropriately. In this study, the stability and accuracy of the calculation were improved by refined grids or using triangular finite elements in the area where the topography is irregular, the current is complex, and/or sedimentation changes greatly. We also tried to avoid using obtuse angles or small acute angles. According to these principles (Zhang 2007), the grids in the computational region were divided as shown in Fig. 1.

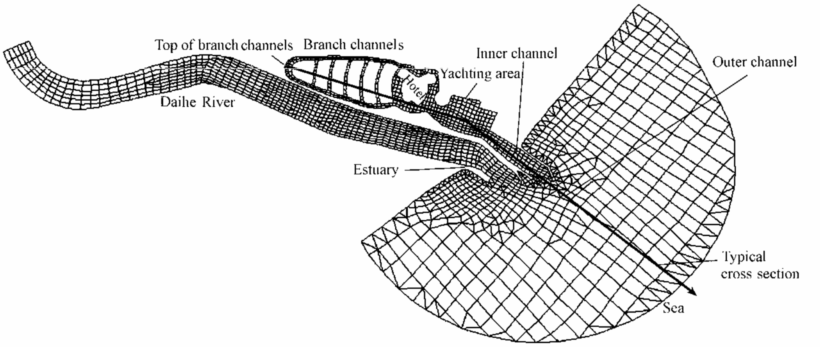

Fig. 1 Border features and grids in computational region

3 Conditions of sediment calculation and calculation cases

3.1 Tidal conditions

Based on a situation of about 90% of the sediment discharge of the Daihe River occurring in July and August every year, and the high tide occurring from July to September, the typical tide periods in 2007 were formulated as follows: spring tide in the flood season, neap tide in the flood season, spring tide in the dry season, and neap tide in the dry season. In this study, the typical tidal hydrograph was obtained by interpolation and converted into an elevation system developed in 1985. The average tidal heights during spring and neap tide periods were, respectively, 0.31 m and 0.25 m in July (flood season), −0.27 m and −0.21 m in January (dry season), and 0.106 m and −0.017 m in April (normal season). The water regime conditions and flow data of the Daihe River were as follows: the annual average flow of the normal precipitation years was 0.23 m^3/s in January, 0.17 m^3/s in April, and 6.85 m^3/s in July. The annual average flow in July during a wet year with floods of 5-, 10-, and 20-year frequencies were 3.23 m^3/s, 7.73 m^3/s, and 10.52 m^3/s, respectively.

3.2 Water regime conditions of Daihe River

Based on a situation that about 90% of the sediment discharge of the Daihe River occurring in July and August every year, and a water volume in the two months accounting for 70% of every year, the calculation conditions were chosen as follows: the average flow data in July over many years and the monthly average flow data with floods of 5-, 10-, and 20-year frequencies, as well as the average flow data in January and April over many years. The peak flows of floods of 5- and 20-year frequencies were 540 m^3/s and 1 225 m^3/s, respectively (Wang and Zhang 1999). The deposition of sediment over a 5-day flood process was simulated by hydrologic analogy.

3.3 Roughness and sediment conditions

A roughness of 0.025 was selected for the river and seabed. A roughness of 0.035 was selected for the floating yachting area.

According to the principle that high flow brings more sediment, the average concentration of the sediment does not change when flows are changing. When flows increase, the sediment increases too. Based on sediment data from other rivers, an average diameter of 0.03 mm (between the average particle size of 0.045 mm and median diameter of 0.021 mm) was chosen for the suspended sediment load in the Daihe River. The sediment discharge of the suspended load was substituted by the total sediment discharge. The sediment discharge of the bed load was not considered in isolation (Hu et al. 2009).

An average concentration of sediment in July (0.83 kg/m^3) and 5 kg/m^3 was selected for the simulation of a 5-year frequency flood (over a 5-day flood peak process). A concentration of 5 kg/m^3 was assumed to be the greatest concentration of sediment. The simulation of a 20-year frequency flood (over a 5-day flood peak process) used the average sediment concentration of 5 kg/m^3, which was assumed to be the greatest concentration of sediment (Shen et al. 2008).

4 Analysis of simulation results

4.1 Distribution of sediment deposition thickness

Fig. 2 is the sediment deposition thickness distribution of five days of flows in the spring tide period of the flood season. It can be inferred from Fig. 2 that, in the most dangerous state, on the eastern side of the hotel, in the yachting area, in the main channel, and in the estuary, the sediment deposition thickness in the spring tide period lasting five days is 1.5 cm to 2 cm. The accumulated sediment deposition thickness in July is 9 cm to 12 cm. On the western side of the hotel, in part of the branch channels, and in part of the outer channel, the sediment deposition thickness is 0.5 cm to 1.5 cm (over five days). The accumulated sediment thickness in July is 3 cm to 9 cm.

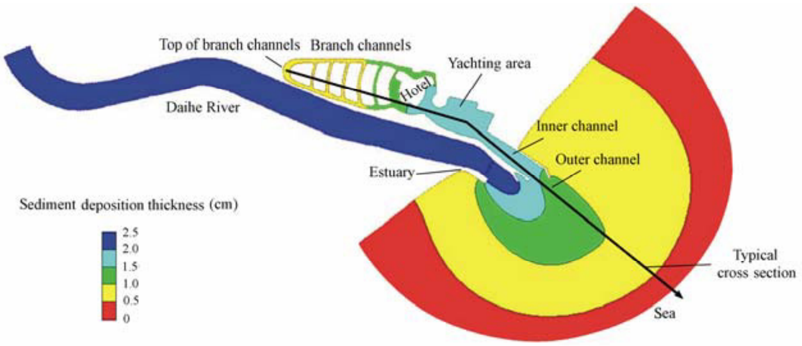

Fig. 2 Five-day deposition thickness distribution of spring tide period in flood season

The area on the eastern side of the hotel, around the yachting area, in the main channel, and in the estuary, is large. The water is deep, and the flow velocity is low. The sediment concentration is high, the hydraulic retention time is long, and sediment is easily deposited. The sediment concentration on the western side of the hotel and in part of the branch channels is relatively low; the velocity is low, and sediment is not easily deposited. From the estuary to the outer channel, the flow velocity is high. The concentration of sediment is low, and the deposition thickness attenuates gradually toward the open sea.

4.2 Analysis of sediment deposition thickness in flood season

From Fig. 3 and Fig. 4 we can see that, at the typical cross sections shown in Fig. 1 and Fig. 2, the sediment deposition thickness is proportional to the average flow in July (in normal precipitation years) and the monthly average flow with floods of a 5-year frequency, 10-year frequency, and 20-year frequency in the neap tide and spring tide periods of wet years. This accords with the principle that high flow brings more sediment. The maximum sediment deposition thickness appears in the yachting area (about 850 m to 1 100 m in the x direction, as shown in Fig. 3). The sediment deposition is very thin in part of the project area (about 0 m to 600 m in the x direction). The causes of the distribution of the sediment deposition thickness were analyzed. The yachting area has high sediment concentration and small flows, enhancing sedimentation. The sediment concentration of the water on both sides of the hotel (about 700 m to 850 m in the x direction) is high, and the flow velocity is low, which also enhances sedimentation. The sediment concentration in the main channel (about 1 100 m to 1 400 m in the x direction) is high, but the flow velocity is slightly higher, so the sedimentation is accordingly slightly thicker.

4.3 Analysis of sediment deposition thickness in normal and dry seasons

As can be seen from Fig. 5, at the typical cross sections, there is no sediment in the Daihe River during the spring and neap tides in normal and dry seasons. The distribution pattern of the sediment deposition is such that the sediment deposition thickness on the eastern side of the hotel, in the yachting area, and in the main channel is largest; the sediment deposition thickness on the western side of the hotel and in the project area is large; and the deposition thickness of sediment from the estuary (about 1 500 m in the x direction) to the sea is attenuating, and in dynamic balance in the sea (about 1 500 m to 2 000 m in the x direction). The sediment deposition thickness in the normal season (April) is smaller than in the dry season (January). From November to the next April, there is no sediment discharge in the Daihe River. During this period, the sedimentation mainly comes from the uneven sedimentation of the Daihe River in the flood season. Under the influence of tides and currents, it is deposited in the project area with lower flow velocity.

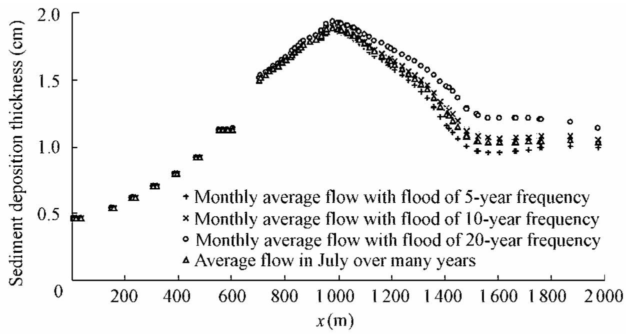

Fig. 3 Distribution of deposition thickness with five days of average flow during spring tide of flood (starting point in *x* direction is where top of branch channels is located)

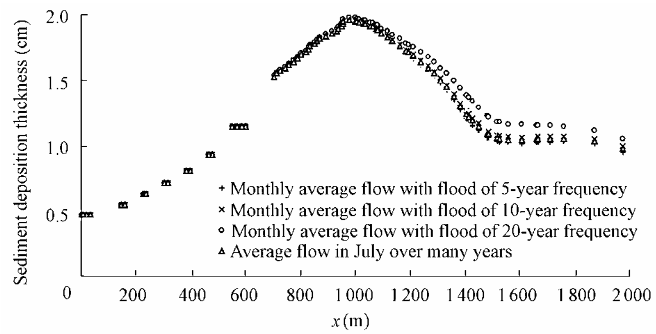

Fig. 4 Distribution of deposition thickness with five days of average flow during neap tide of flood

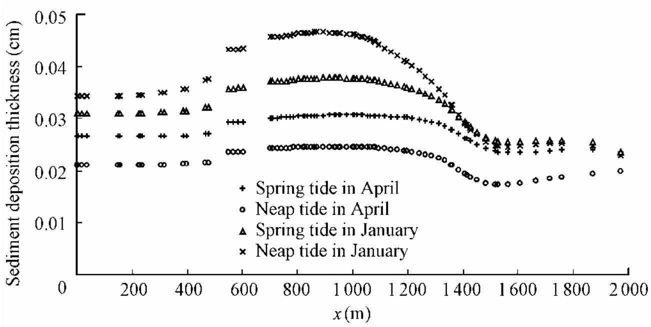

Fig. 5 Distribution of deposition thickness without sand coming into Daihe River for five days during spring and neap tides in normal and dry seasons

4.4 Estimate of annual sediment deposition thickness

According to the monthly sediment deposition thickness scope and the distribution ratio of the average sediment discharge in the Daihe River over many years, the relationship between sediment discharge in July and deposition thickness was used to estimate the thickness of sediment from May to October. The sediment deposition thickness was estimated according to three months of the normal season and three months of the dry season, so we could obtain the sediment deposition thickness scope over a year (2007). The annual deposition thickness ranges between 6.8 cm to 18.9 cm on the western side of the hotel and in the project area; the annual deposition thickness ranges between 18.9 cm to 25.1 cm on the eastern side of the hotel, in the yachting area, and in the main channel.

4.5 Simulation of sedimentation for flood peak process

At the typical cross sections, the sediment deposition thickness is large near the estuary and in the main channel (Figs. 6 and 7). After a flood (with a 5-year frequency) containing 0.83 kg/m^3 of sediment lasts five days, the maximum sediment deposition thickness is 5 cm. After a flood (with a 5-year frequency) containing 5 kg/m^3 of sediment lasts five days, the maximum sediment deposition thickness is 24 cm (during neap tide) or 23 cm (during spring tide). After a flood (with a 20-year frequency) containing 5 kg/m^3 of sediment lasts five days, the maximum sediment deposition thickness is 56 cm (during neap tide) or 42 cm (during spring tide). The maximum value appears in the main channel. The main causes of sediment deposition in the yachting area, the main channel, and the project area are the floods, which contain a high concentration of sediment.

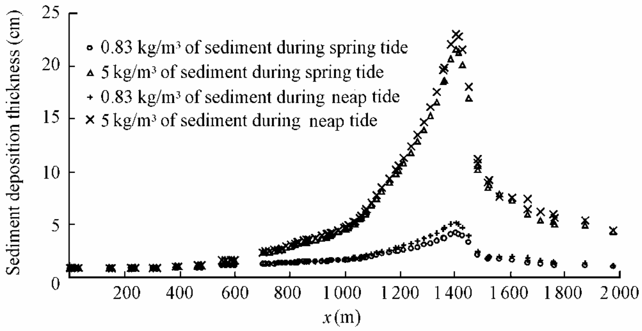

Fig. 6 Distribution of deposition thickness with flood of 5-year frequency over 5-day flood peak process

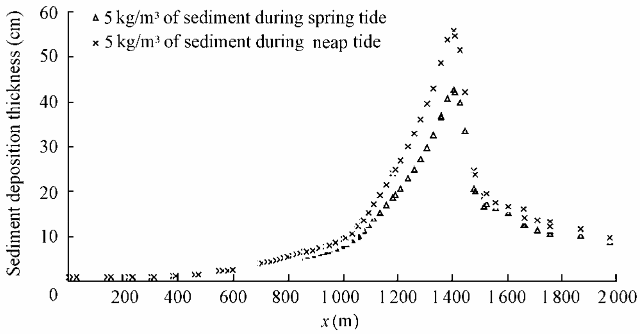

Fig. 7 Distribution of deposition thickness with flood of 20-year frequency over 5-day flood peak process

5 Model verification

Because of the relative deficiency of sedimentation data for the Daihe River, the model was verified under these conditions with annual average sediment discharge. To enhance the simulation guarantee rate, a concentration of 0.05 kg/m^3 (Lu and Sun 1997) was used, which was the initial content of sediment in the Bohai Sea. A sediment density of 2.65 g/cm^3 (Pang and Yang 2000) was used in this study. The simulation results show that the annual average sediment discharge in the Daihe River is 27 500 t, which is acceptably close to the value of 26 500 t from Lu and Sun (1997). The simulation error is 3.77%, which accords with the requirements of engineering research.

6 Conclusions and discussion

The analysis of sediment hydrodynamics simulation showed the following: The range of the annual sediment deposition thickness is 6.8 cm to 18.9 cm on the western side of the hotel and in the project area, and 18.9 cm to 25.1 cm on the eastern side of the hotel, in the yachting area, and in the main channel. The maximum changes of sediment deposition thickness are near the estuary and in the main channel, and the changes are small in the project area. The sediment deposition in the yachting area, the main channel, and the project area is due to the floods, which contain a high concentration of sediment.

To sum up, the sediment deposition thickness is relatively small in the project area. In order to deal with sedimentation, we can first excavate and dredge the channel regularly to solve the problem. Secondly, we should use the gradual massing transition where the bed changes significantly and set signs where the depth changes. In addition, we should completely clean the channel of pollutants and construction waste after project construction. During project operation periods, we should cut off the sediment source to the project area, especially the rain silt, falling dust, blown sand, and dust from urban greening. All of the above are effective and feasible measures for reducing the sediment.

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